Description

Selecting One of Multiple Antennas to Receive Signals in a Wireless Packet Network

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] The present application is related to and claims priority from the co-pending U.S. Provisional Patent Application Serial No.: 60/454,862, entitled, "Optimal Algorithm for Antenna Selection Diversity in IEEE 802.11b/g Wireless Networks@, Attorney Docket Number: TI-36044PS, filed on 03/13/2003, naming as inventors: RAMAKRISHNAN et al, and is incorporated in its entirety herewith.

BACKGROUND OF INVENTION

[0002] *Field of the Invention*

[0003] The present invention relates to wireless communications, and more specifically to a method and apparatus for selecting one of multiple antennas to receive signals in a wireless packet network.

[0005] Data packets are often transmitted using wireless technologies. For example, a stream of bits representing voice may be transmitted in the form of packets using standards such as CDMA. In general, a packet contains a payload portion representing the data of interest to be transported, and a non-payload portion (containing subportions such as preamble, postamble, midamble, training sequences).

[0006] A typical sending system transmits each packet in several directions (angles). Each transmitted signal may be bounced (reflected) by several surfaces present in a corresponding path before reaching a receiving system. Before reaching the receiving system, each reflected signal may undergo different degrees of attenuation, phase rotations and be subject to different noise levels depending on various factors as is well known in the relevant arts.

[0007] A receiving system may employ multiple antennas to receive packets. In general, multiple antennas are employed such that at least one of the antennas is located in a path of a signal which is more conducive (e.g., high strength/amplitude) for the recovery of the encoded data, and it is generally desirable that the signal received by such an an-

tenna (in the path of the strong signal) be examined to re-cover the encoded bits of the packet.

[0008] In situations where only two antennas are used, the two antennas may be separated by a distance of $\square$ /2, wherein '$\square$ represents the wavelength corresponding to frequency of operation of the communication system. Accordingly, there is a general need to select one among multiple an-tennas when receiving a packet using wireless technolo-gies.

BRIEF DESCRIPTION OF DRAWINGS

[0009] The present invention will be described with reference to the following accompanying drawings.

[0010] Figure (Fig.)1 is a block diagram illustrating the details of an example environment in which present can be imple-mented.

[0011] Figure 2 is a flow-chart illustrating the details of a method using which one of multiple antennas receiving a signal in a wireless packet network may be selected according to an aspect of the present invention.

[0012] Figure 3 is a block diagram illustrating the details of an embodiment of a receiver block implemented according to an aspect of present invention.

[0013] Figures 4A, 4B, and 4C contain equations forming part of

the theoretical background for a selection approach employed in an embodiment of the present invention.

[0014] Figure 5 is a diagram illustrating the program logic based on which a selector block selects an antenna receiving signal more conducive for recovery in one embodiment.

[0015] In the drawings, like reference numbers generally indicate identical, functionally similar, and/or structurally similar elements. The drawing in which an element first appears is indicated by the leftmost digit(s) in the corresponding reference number.

DETAILED DESCRIPTION

[0016] *1. Overview*

[0017] A receiver implemented according to an aspect of the present invention processes a signal received on each antenna to determine multiple parameters associated with the corresponding antenna, and selects one of the antennas based on the parameters. In one embodiment, the parameters determined for each antenna include the strength of the signal received from the antenna and a correlation value representing the similarity of a portion of a received signal with an expected signal according to a pre-defined protocol.

[0018] In an implementation described below, the expected signal corresponds to a Barker Sequence (well known in the relevant arts), and a digital value (representing discrete signal levels) generated from the portion of the received signal is compared with the Barker sequence to determine the correlation value.

[0019] By using such multiple parameters to select among antennas, the antenna receiving a signal most conducive to recovery (with high SNR) of the encoded data may be selected. The above approach of selecting an antenna may be repeated for receiving each packet since the determination of the specific antenna may be performed based on the preamble of each packet.

[0020] Several aspects of the invention are described below with reference to examples for illustration. It should be understood that numerous specific details, relationships, and methods are set forth to provide a full understanding of the invention. One skilled in the relevant art, however, will readily recognize that the invention can be practiced without one or more of the specific details, or with other methods, etc. In other instances, wellstructures or operations are not shown in detail to avoid obscuring the invention.

[0021] *2. Example Environment*

[0022] Figure 1 is a block diagram illustrating the details of an example environment in which the present invention can be implemented. The environment is shown containing source block 110, transmitter 130, transmitting antenna 140, receiving antennas 150 and 160, receiver 170, and destination block 190. Each block is described below in further detail.

[0023] The environment is shown containing only a few representative components for illustration. However, typical environments contain many such components and such environments are also contemplated to be within the scope and spirit of various aspects of the present invention. In addition, merely for conciseness, the description is provided with reference to two receiving antennas only. However, more than two antennas may be used without departing from the scope and spirit of various aspects of the present invention, as will be relevant to one skilled in the relevant art by reading the disclosure provided herein.

[0024] Source block 110 may contain (e.g., execute) applications generating data bits destined to destination block 190. Destination block 190 receives the data bits on path 179 via transmitter 130 and receiver 170. Similarly (even

though not illustrated in the drawing, in the interest of conciseness), destination block 190 may send data packets to source block 110. The data bits thus exchanged can form the basis for various user applications. Source block 110 and transmitter 130 together form a sender system, and receiver 170 and destination block 190 form a receiver system in the depicted scenario.

[0025] Transmitter 130 receives a sequence of data bits from source block 110, and transmits the received bits in the form of packets according to a pre-specified wireless technology (e.g., direct sequence spread spectrum (DSSS)). Each packet may be encoded in multiple signals/samples which are transmitted in all directions. Transmitter 130, source block 110, and destination block 190 may be implemented in a known way.

[0026] Receiver 170 is shown connected to multiple antennas (150 and 160), and selects the signal received on one of the antennas to recover the data bits transmitted by transmitter 130. The recovered bits are provided on path 179. In general, receiver 170 selects one of several available antennas based on multiple parameters characterizing each signal received by a corresponding antenna as described below in more detail with respect to several ex-

amples.

[0027]   *3. Method*

[0028]   Figure 2 is a flow-chart illustrating the details of a method using which a receiver may select one of multiple antennas according to an aspect of the present invention. The method is described with reference to Figure 1 merely for illustration. However, the method may be implemented in other environments as well. The method begins in step 201, in which control immediately passes to step 210.

[0029]   In step 210, receiver 170 examines a signal portion corresponding to a non-payload portion to determine the strength of the received signal, and a correlation value for each of the antennas 150 and 160. Here the strength of the signal received on each antenna measures the power/ energy due to the desired signal and receiver noise and it may be determined using one of several known approaches. The correlation value represents the similarity of a portion of a received signal with an expected signal according to a pre-defined protocol.

[0030]   As is well known, many wireless standards (e.g., IEEE 802.11b) provide a preamble associated with each packet. The preamble generally enables the receivers to synchronize the sampling points and perform various other ad-

justments (e.g., determining an amplification factor using automatic gain control (AGC) to accurately recover the data bits that follow the preamble). As described in further detail below, in an example embodiment, the gain factor is used to determine the strength of the signal received on each antenna, and the Barker Sequence in the preamble is used to determine the correlation values. While the description is provided with reference to examining the preamble portion of a received packet, it should be appreciated that other non-payload portions may also be examined to select the appropriate antenna according to various aspects of the present invention.

[0031] In step 240, receiver 170 selects the antenna to receive the packet based on the parameters (values) determined for each antenna. In general, an antenna receiving the signal with high signal strength and "good" correlation values is considered to be more conducive to recover the data. The manner in which the two parameters can be used in selecting an antenna is described in sections below with examples.

[0032] In step 280, receiver 170 recovers the remaining data bits in the packet based on the signal received on the selected antenna. Steps 210 through 280 may be repeated for each

packet. Thus, the approach of Figure 2 can be used to employ multiple antennas and recover data bits of a packet from an antenna receiving a signal potentially most conducive to recovery. The description is continued with reference to details of additional embodiments of receiver 170.

[0033] *4. Receiver*

[0034] Figure 3 is a block diagram illustrating an embodiment of receiver implemented according to an aspect of present invention. Receiver 170 is shown containing switch 310, variable gain amplifier 320, analog-to-digital converter (ADC) 340, automatic gain control block (AGC) 350, Barker matching filter (BMF) 360, slicer 370, and selector block 390. Each block is described below in further detail.

[0035] Selector block 390 causes switch 310 to connect either antenna 150 or antenna 160 to path 312.general, when a preamble for a packet is being received, selector block 390 selects each one of the antennas to measure the corresponding parameters defined above. A specific one of the antennas is then selected as being most conducive to recover the data in the payload portion. When the remaining part of the data packet (including payload) is being later received, the selected antenna is caused to be con-

nected to path 312.

[0036] With respect to the selection of the specific one of the antennas, in an embodiment implemented using IEEE 802.11b/g standard, while receiving preamble, selector block 390 first connects one of the two antennas 150 and 160 to path 312, and measures the correlation values and strength (example "parameter values") of the signal being received on the connected antenna. Selector block 390 then connects the other antenna to measure the related parameter values. One of the two antennas is then selected for receiving the packet data based on the measured parameter values.

[0037] Amplifier 320 filters and amplifies the signal received on path 312. The degree of amplification is determined by an amplification factor received from AGC 350. The amplification factor is generally set to a value such that the full range of ADC 340 is used. Though shown as one unit, amplifier 320 may contain a series of amplifier and frequency selective filter circuit combination to remove various undesirable components present along with the base band signal (transmitted signal). Amplifier 320 may be implemented in a known way. Switch 310 connects either antenna 150 or antenna 160 to path 312 under the con-

trol of selector 390, and may be implemented in a known way.

[0038] AGC 350 examines the output of ADC 340 when the preamble is being received, and determines the amplification factor. In general, if the signal at the input of the receiver is of lower strength, then higher amplification factor is required to amplify the signal to a desired level. As noted above, the respective amplification factor may be determined for the signals received on both antennas 150 and 160, and provided to selector block 390. Once one of the antennas is selected, the associated amplification factor is provided to amplifier 320. AGC 350 (including the storage required to store the amplification factors) may also be implemented in a known way.

[0039] ADC 340 samples the signal received from amplifier 320 to generate sampled data elements. In an embodiment, each sampled data element comprises multiple bits, which are passed to BMF 360 for further processing. ADC 340 may be implemented in a known way.

[0040] BMF (Barker match filter) 360 generates a correlation value associated with each data bit in the received signal. As is well known and described in IEEE 802.11b/g standard, transmitted signal equals the 11 sample sequence {1, -1,

1, 1, –1, 1, 1, 1, –1, –1, –1} (Barker sequence) when a data bit of 1 is to be encoded, and {–1, 1, –1, –1, 1, –1, –1, –1, 1, 1, 1} (negation of Barker sequence) when a data bit of 0 is to be encoded. The pre-amble associated with each packet also encodes a sequence of bits. Thus, by examining the 11-bit code generated associated with each antenna, the corresponding correlation values may be generated.

[0041] While the embodiments here are described with reference to Barker sequences merely for illustration, it should be understood that alternative implementations may be provided using any spread sequences (e.g., as in DS-CDMA) well known in the relevant arts.In such a situation, a corresponding matching filter needs to be generally implemented. Such implementations are contemplated to be covered by various aspects of the present invention.

[0042] BMF filter 360 generates a correlation value corresponding to each data bit received. In the embodiment of Figure 3, the correlation value represents a count indicating the number of matching bitsthe number of non-matching bits for the code corresponding to a data bit of 1. A correlation value of +11 indicates that a data bit of 1 is received, and a correlation value of indicates that a data bit of 0 is

received.

[0043] It should be understood that BMF filter 360 merely represents an example component implementing an example approach to generating a correlation value. Correlation values may be determined using other techniques/approaches. For example, instead of using digital values (or discrete levels) as described above, comparison can be performed on analog signals. Such implementations will be apparent to one skilled in the relevant arts by reading the disclosure provided herein, and are contemplated to be covered by various aspects of the present invention.

[0044] The correlation values may be used for selecting the antenna and the value of the bit. In one embodiment, the amplification factor determined by AGC 350 is also used as another factor in determining the received signal strength. In general, BMF filter 360 and AGC 350 together represent an example parameters generation block, which determines various parameters used to select the specific one of the available antennas.

[0045] Slicer 370 generates data bits from the correlation values received from BMF 360. In an embodiment, a value of 1 is deemed to be present for a positive correlation value (+1 through +11) and a 0 is deemed to be present for a nega-

tive correlation value (–1 to –11). The digital bits thus generated are transferred on path 179 to destination block 190. While slicer 370 is described as recovering a single bit each time, it may be appreciated that the received signal may containcontaining multiple bits, and implementation of such extensions will be apparent to one skilled in the relevant arts by reading the disclosure provided herein.

[0046] In addition, components such as filter 320, ADC 340 and BMF 360 are shown following switch 310, which generally reduces the overall cost of implementation (since the components following the switch are shared by all antennas). However, alternative embodiments may be implemented in which some or all of such components are before switch according to various aspects of the present invention.

[0047] As noted above, selector block 390 needs to select one of the antennas, which is receiving a signal most conducive (high SNR, generally) to accurate recovery of data bits. The general theoretical basis (in an embodiment) for selecting an antenna receiving a signal conducive for recovery is described below

[0048] *5. Theoretical Background*

[0049] For purposes of understanding the theoretical background, it is assumed that α_i is the attenuation of the signal received in the ith antenna and n_i is the noise of variance σ^2_i, added to the signal received from the ith antenna (for illustration, only two antennas 150 and 160 are considered). The different noise powers may be modeled on the two antennas (150 and 160) by assuming that σ_i^2s are independent and uniformly distributed in [a, b], wherein a, b > 0. A factor K may be defined to equal $^b/_a$. The ratio of the noise variances obeys the boundary condition represented by Equation (1) of Figures 4A, 4B and 4C (collectively referred to as Figure 4 in the description below).

[0050] The gain G_i (provided by amplifier 320, controlled by AGC 350) gains up the in-band signal and the corresponding noise to a desired set point for the ith antenna. It may be assumed that the antennas are well separated and the signals received on the two antennas 150 and 160 undergo independent fades.

[0051] The symbol s_k is spread by the Barker sequence of length N and can be represented in vector notation as shown in Equation (2) of Figure 4, wherein b represents the Barker sequence in vector notation.

[0052] The signal ($y_{1,k}$ and $y_{2,k}$) at the output of AGC 350 corresponding to signal (represented symbol x_k of Equation (2)) received by antennas 150 and 160 is as shown respectively in Equations (3) and (4) of Figure 4, wherein α_i represents the channel gain for the ith (equals 1 and 2 corresponding to antennas 150 and 160) path, $n_{i,k}$ represents the noise vector received at the ith antenna for k^{th} symbol and is of N(= 11 in the example above) chip duration (time duration for each of 11 pulses in the illustrative example) and G_i (or AGC_i) is the power gain given by the AGC 350 for the signal from the ith antenna.

[0053] Noise is assumed to be additive white Gaussian noise (AWGN) and has the probability density function (PDF) $N(0, \sigma^2_i)$ in the ith antenna. Symbol s_k is got from a PSK constellation. AGC 350 sets the amplifier's power gain such that the amplifier (320) output has power equal to P and the power gains of the ith antenna is as shown in Equation (5) of Figure 4. Power gain of Equation (5) may be re-written resulting in Equation (6) that follows from the definition of SNR.

[0054] The signal after amplification (by amplifier 320) is passed to the Barker matched filter (BMF 360), the output of which is sampled appropriately to get the peak of the cor-

relation. Since the phase of s_k is unknown (as, the exact position of the bit being accessed in the header (pre-amble) is not known), the power at the output of BMF 360 may be examined and is represented by Equation (7) shown in Figure 4. Substituting for G_i (from Equation (6)) in Equation (7), the resulting Equation (8) is also shown in Figure 4.

[0055] The sum of the first two terms in the RHS of Equation (8) is a Gaussian random variable having a distribution of $N((\rho_i/1+\rho_i) N^2 P, 2N^3 P^2 (\rho_i /(1+\rho_i)^2))$ and the third term is (chi-squared) X^2 distributed with mean and standard deviation of the X^2 process being $\frac{NP}{1+\rho i}$. The ratio of the variances of the Gaussian process to the X^2 process is $2N\rho$, wherein $N = 11$ for the barker sequence. It implies that at reasonably high SNRs (say $\rho > -3db$), X^2 noise process may be neglected. The X^2 process may be approximated by its mean and thus, the correlation power, given the SNR, is distributed as $N((N\rho_i+1/1+\rho_i) NP, 2N^3 P^2 (\rho_i / (1+\rho_i)^2))$.

[0056] Thus, a mathematical signal model of receiver 170 may be modeled. The description is continued with reference to selection of an antenna using such a model.

[0057] *6. Optimal Antenna Selection*

[0058] The basis for selecting an antenna with the higher SNR, given the corresponding correlation values and AGC gains of both the antennas (150 and 160), is described below. As both antennas 150 and 160 are equally likely to have a good/acceptable SNR (thereby being conducive to recovering the data bits), the optimal rule is the Maximum-Likelihood (ML) criterion (well-known in the relevant arts), according to which antenna 150 may be selected, if the condition below is satisfied, otherwise antenna 160 may be selected.

[0059] $P([C1;C2;G1;G2] / \rho 1 > \rho 2) > P([C1;C2;G1;G2] / \rho 2 > \rho 1)$ (8A)

[0060] Although strength of the signal received by an antenna can be represented as a Rayleigh or Rician random variable (both well known in the relevant arts) and the parameters of the process at the receiver are usually not known. Only ρ_i; $vi = 1; 2$ is i.i.d (independent and identically distributed) may be assumed at the receiver. Now the left hand side (LHS) of the Equation (8A) can be written as shown in Equation (9) of Figure 4.

[0061] Now given the SNRs, the correlations and the gains are independent of one another. From this property and Equation (6), the LHS of Equation (8A shown above) can be

written as shown in Equation (10) of Figure 4, wherein $f_{(x)}(x/a)$ represents the conditional PDF of the random variable x given a. Given $\rho_1, \rho_2, \sigma^2_1$ and σ^2_2, G_1 and G_2 are deterministic (from Equation (6)) it may be understood that the corresponding PDF is a 2-d delta function.

[0062] For $\square_1 > \square_2$, we need $(^{G2}/_{G1}) > (^{\sigma^2 1}/_{\sigma 2 2})$. From Equation (1), this is true if $(^{G2}/_{G1}) > K$ and false if $(^{G2}/_{G1}) < (^1/_K)$. If $(^{G2}/_{G1}) > K$, and $\rho_1 > \rho_2$ select antenna 150, and if $(^{G2}/_{G1}) < ^1/_K$, and $\rho_1 < \rho_2$ select antenna 160. If $(^1/_K) = < (^{G2}/_{G1}) <= K$, then from the fact that $a < \square^2_1, \square^2_2 < b$, the boundary conditions corresponding to ρ_1 and ρ_2 for LHS may be represented by Equations (13), (14), (15) and (16) shown in Figure 4.

[0063] Simplifying the constraints, the LHS may be written as shown in Equation (17) of Figure 4. Similarly, simplifying the right hand side (RHS), the ML rule (when $(^1/_K) = < (^{G2}/_{G1}) <= K$) is as shown in Equation (18) of Figure 4.

[0064] In order to simplify this expression, let $G_{max} = ^P/_a$, then $^P/_b = ^{Gmax}/_K$ and let $g_1 = ^{G1}/_{GmaxK}$ and $g_2 = ^{G2}/_{GmaxK}$, then $^{G1}/_{G2} = ^{g1}/_{g2}$. Then Equation (18) may be written as shown in Equation (19) of Figure 4.

[0065] As there is no closed form for the integral shown in Equation (19), numerical integration approaches may be ap-

plied. In one embodiment, the range of SNR that may be considered equals 0 to 30 dB. It is assumed that the SNRs are uniform over this range (0 to 30 dB). The corresponding integrals may be evaluated numerically.

[0066] The optimal ML rule may need to be implemented as a huge table with entries for different possible correlation and gain values. In one embodiment, by observing the table values, the following approach (of Figure 5) was determined to be the optimal approach, and accordingly the selection may be implemented according to the corresponding logic. In the approach described below, various variables/functions m1, m2, c1 and c2 are used. These variables/functions may be determined while developing the approach, and the specific values generally depend on the value of K.

[0067] Assuming for illustration that K = 6dB and and that T1 = 1dB and T2 = −7dB. For g2/g1 = +1dB, we get m1(1) = 13.75, m2(1) = 1:5, c1 (1) = 441 and c2(1) = 47. From this it may be observed that only for very low values of g, do we get a range where antenna 160 is selected. As the value of g increases, the range decreases and antenna 150 is selected. This is because low g corresponds to a higher SNR (all possible values of SNR are "high") and the corre-

lations are expected to be around μ_∞.

[0068] Thus, if C1 is away from μ_∞ and C2 is close to μ_∞, antenna 160 is selected. But as the gain increases, the SNR decreases and the spread of the correlation values increases. Hence antenna 160 is selected if C1 is more away from μ_∞ than C2 is closer to it. This is reflected in the fact that m1 is substantially greater that m2 in the above example. As g increases even further, the confidence on the correlation values falls rapidly and hence antenna 160 is selected, just on the basis of g2=g1 = 1. For the case of g2=g1 = -1dB, similar results are attained, and that m1(-1) = 1.25, m2(-1) = 17, c1(-1) = 45:5 and c2(-1) = 540.

[0069] The analysis provided above is simplified to provide the following implementation described with reference to Figure 5 below.

[0070] *7. Implementation*

[0071] Figure 5 contains lines 501–523 illustrating the manner in which selector block 390 maybe implemented to select either antenna 150 or 160 depending on the values of two measured parameters. The values of AGC1, AGC2, C1, and C2 noted above may be provided to selector block 390. The mean(mu) of the Gaussian distribution of correlation

values may be determined as equaling $N^2 \times P$ (wherein N=11 if a 11-bit Barker sequence is used as a preamble, and P is the power output of amplifier 320). The values of T1, T2, m1, m2, c1, and c2 may be determined/estimated and provided (stored) to selector block 390 prior to selection of antenna.

[0072] Selector block 390 may operate according to the instructions in lines 501–523 to select one of the two antennas. Each instruction is self-explanatory , and is not repeated here in the interest of conciseness. However, broadly, it may be observed that selector block 390 operates according to the following four rules.

[0073] Rule 1: When the difference in AGC1(in dB) and AGC2(in dB) values is large (compared to difference in threshold T1), the selection of antenna is based on the difference in gains (correlation values may not be considered for selecting an antenna). An antenna receiving a signal requiring lower gain factor may be selected (as strength of such a signal may be higher).

[0074] Rule 2: When the absolute value of difference between AGC1 and AGC2 values is small (less than T1, but not equal to zero), the correlation values are given a large weight as long as one of them is close to μ_∞ and the other

is away from μ_∞. In this case, the correlation that is close to μ_∞ has a higher SNR with a large probability and hence that antenna is selected.

[0075] Rule 3: When AGC1 and AGC2 values are equal (i.e., difference between AGC1 and AGC2 equals zero), and if AGC1 and AGC2 are high (greater than gain threshold T2), then select antenna whose correlation value is closer to μ_∞, as similar logic as Rule 2 may be applied to select one of the antennas.

[0076] Rule 4: When AGC1 and AGC2 values are equal, and if AGC1 and AGC2 are low (less than T2), an antenna receiving a signal representing higher correlation value may be selected.

[0077] Thus, an antenna receiving a signal most conducive for recovery may be selected while receiving each data packet.OLE_LINK1

[0078] *9. Conclusion*

[0079] While various embodiments of the present invention have been described above, it should be understood that they have been presented by way of example only, and not limitation. Thus, the breadth and scope of the present invention should not be limited by any of the above described exemplary embodiments, but should be defined

only in accordance with the following claims and their equivalents.